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Studies of the Coastal Morphology on Surtsey Island

JOHN O. NORRMAN

OFFICE OF AEROSPACE RESEARCH
United States Air Force



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**Studies of the Coastal Morphology
on Surtsey Island**

JOHN O. NORRMAN

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Abstract

Investigations on the shore and offshore morphology of the volcanic island of Surtsey off the southeastern coast of Iceland are reported. The volcanic activity that started as a submarine explosion in November 1963 ended in June 1967. A photogrammetric map of the island is in preparation. During the winter 1967/68 there was a rapid retreat of the lava cliff on the southern coast. The cliff is 10-15 m in height. The maximum retreat was 140 m and the average retreat about 75 m. The amount of lava removed by erosion is estimated at 2 million cubic meters.

The shoals of former cinder-cone islands (Surtla, Syrtlingur, and Jólnir), contemporaneously built up, were found to have been abraded during the last winter. The plateaus of Jólnir and Surtla had been lowered several meters.

The submarine slopes of Surtsey were investigated by SCUBA diving down to a maximum of 40 m in depth. The sandy material of the slopes of the northern point is deposited at the frictional angle of repose. There is active avalanching on these slopes. On the slopes of the southern coast angular blocks dominate. Some of the blocks are more than 5 m in diameter. The future development of the island will be recorded by aerial photography and successive surveys of fixed traverses.

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Studies of the Coastal Morphology of Surtsey Island

I. INTRODUCTION

The volcanic island of Surtsey off Iceland's southeast coast is under legal protection. It is possible to make a landing only with special permission. Research projects concerning the island must be approved by Surtseyjarfélagið (The Surtsey Research Society) in Reykjavík. Research activity is divided into different sections, and the author was assigned responsibility for coastal morphology research. A field reconnaissance was carried out in September, 1967, and in June, 1968, measurements were taken on grid bases for a precise photo-topographic map, coastal morphological measurements, collection of samples, and a clear inventory of the submarine morphology down to a maximum of 40 meters. During the latest summer's work, fil. lic. T. Alexandersson and fil. kand. T. Lindell accompanied the author in the field. Research has been accomplished with grants from the Naturvetenskapliga Forskningsrådet (Swedish Natural Science Research Council) and Surtseyjarfélagið (The Surtsey Research Society).

(Received for publication 18 March 1970)

2. VOLCANISM SOUTH OF ICELAND

Volcanic eruptions in the sea cause headlines on the front pages of newspapers. During its active eruption period from the first explosions in November, 1963, up to the latest lava flow in the spring of 1967, the volcanic island of Surtsey, just off the southeast coast of Iceland, became a great tourist attraction for the Icelandic trans-Atlantic airlines via Reykjavík. The play of forces which is now developing along the shores of the dormant volcano is also gigantic, but does not have the brilliance of the living volcano.

Surtsey is a part of the Vestmannaeyjar (Vestmann Islands) which is situated on the mid-Atlantic ridge. That ridge runs through the South and North Atlantic in a large S-curve and has a double crest with a central vault valley - a graben. The unstable fault is of utmost importance for the study of continental drift. The fault extends through Iceland and can be followed there in a series of volcanoes which have been active during historical times such as, for example, Hekla, which had its latest eruption in 1947. Other islands on the mid-Atlantic ridge that are characterized by volcanic activity are, for example, Tristan da Cunha in the South Atlantic and the Azores in the North Atlantic.

Surtsey is not a unique occurrence. The main island of the Vestmannaeyjar Archipelago, Heimaey, was built of young volcanoes with the latest eruptions 5000 to 6000 years ago. Heimaey is surrounded by high, steep, small islands, which are called "bird mountains." These are the remnants of volcanoes which for the most part have been broken down by waves, wind and rain. A detailed mapping of the sea carried out in recent years has shown the locations of about 60 submarine volcanic cones (Figure 1). How many of these formerly reached above sea level is not known.

3. DEVELOPMENT OF THE VOLCANO

The eruption of Surtsey began on November 14, 1963. At first a volcanic cone (Surtur Senior) emerged above sea level, consisting only of explosive eruption-products (tephra) with particle size ranging from blocks with a thickness of a meter to powderlike dust. In February, 1964, another explosive cone formed (Surtur Junior), together with the former. Earlier in December an eruption had taken place halfway between Surtsey and the outermost rocky islet. The island which was forming was called Surtla, but it never reached above sea level.

The destructive effect of the waves was very great in the unconsolidated tephra. Surtsey persisted because of the continuous supply of new material (on the average, about $40 \text{ m}^3/\text{second}$).



Figure 1. Central and Western Parts of Westman Islands. Submarine volcanic cones marked in black with summit level in meters below sea level.



Figure 2. Aerial Photograph of Surtsey on July 6, 1968. Size of island 1.6 x 2.0 km. The northern walls of the two primary cinder cones remain, but that of the western younger one is heavily eroded by the sea. The central and southern parts of the island are covered by lava (Figure 3). The northern point is built up by beach drift. Narrow ridge on the point is a remnant of a large slide block that subsided in an early stage of development

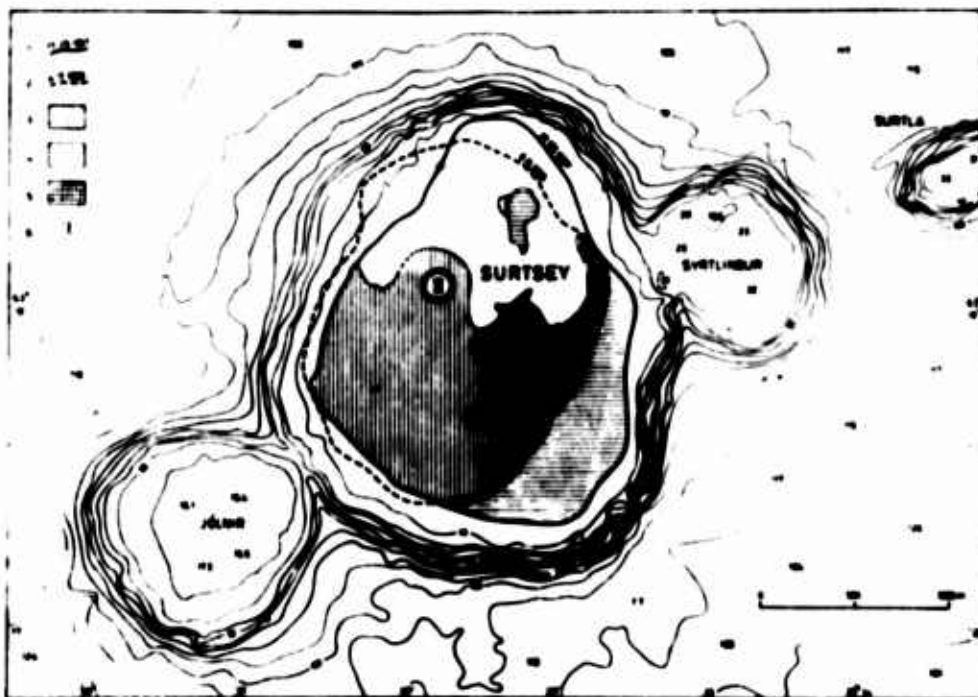


Figure 3. The Lava Fields of Surtsey and the Submarine Topography Around the Island. 1 and II, the craters of Surtur Senior and Junior. 1, coastline of July 17, 1967. 2, coastline of Feb. 6, 1966. 3, 1964/65 lava (from Surtur II). 4, 1966/67 lava (from Surtur I). 5, area of 1964/65 and 1966/67 lava flows. 6, lagoon. Soundings made in July 1967 by B. E. T. Humphrey, R. N. Depth contour interval 10 m. The shoals of Syrtlingur and Jólnir are abraded cindercone islands. Surtla never appeared above sea level

The spring of 1964 brought a new phase, since lava began to flow out of Surtur Senior (sic*) and cover the south side of the island (Figure 3). The glowing lava which reached the sea seems to a large extent to have been changed into lava gravel during the hardening process. During the same spring, an explosion occurred just east of Surtsey and a new island, Syrtlingur, was formed. Syrtlingur never produced any lava. The island reached its greatest size in the beginning of the fall, but was already levelled by wave action by October. In december a new submarine explosion occurred, this time southwest of Surtsey. The newly formed island was named Jólnir - "Christmas Island." Jólnir, too, produced only tephra and was broken down in September, 1965 (sic**), by the first autumn storms. The final activity came from Surtsey's oldest crater, Surtur Senior, from which lava flowed from April (sic***), 1966, to June, 1967.

After more than three years of simultaneous buildup and erosion, the Surtsey island complex and three nearby, aligned, submarine plateaus existed. All eruptions had occurred along the same fault. Surtsey's future existence is totally dependent upon the lava flows which mantle the island south of the Surtur craters.

During the first three years, the development of the coastline was observed by Professor S. Thórarinnsson, Reykjavík, who wrote a report based upon aerial photographs. Certain observations concerning the coastal material were also made, but no quantitative morphological research was done. Generalized photogrammetric contour mapping was carried out in 1965. Echo soundings were taken along a number of traverses around the island in 1966, and in July, 1967, detailed soundings were taken of the submarine slopes and the ocean floor next to them by B. E. T. Humphrey, Royal Navy.

4. EROSION AND CHANGE

The land is affected by the following exogenous processes: weathering, erosion, transportation of material and deposition of material. As the rainwater seeps through Surtsey's tephra cones, mud flows trickle along the sides and give them a characteristic pattern of furrows bordered by banks of dried material (Figures 5 and 11). The wind erodes and transports more material from the cones and from the beach's sandy surface. On dry windy days it is impossible

* Junior.

** 1966.

*** August.



Figure 4. Lava Cliff and Abrasion Terrace on the Southeastern Coast Where the Cliff Retreat was 125 m in the Winter 1967/68

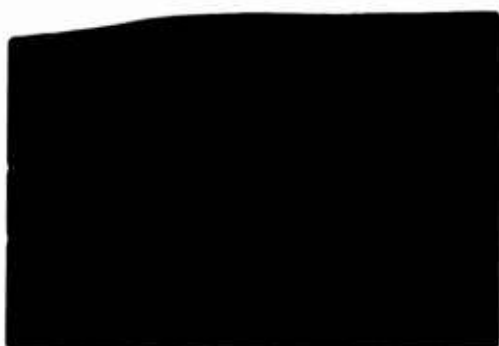


Figure 5. Mudflow Tracks on the Northern Slope of Surtur Junior



Figure 6. The Northern Part of the Eastern Shore Terrace

to walk over the island without sunglasses. The most important source of erosion of Surtsey, however, is the movement of the waves on the coastline.

The wave action against the steep lava cliffs causes pressure shocks which in turn causes cracks in the rigid lava beds, and the outgoing waves take loose pieces of rock along which roll down the submarine slopes (Figure 14). On the lava cover one can see how new cracks develop up to 15 to 20 meters inland. The walls of the cliff that have been undermined by the water break down. During storms the waves throw cubic meter-sized boulders on to the lava surface 10 to 15 meters above sea level (Figure 10). Below the cliff loose boulders are worn against each other and against the bottom layer. In this manner a wave-eroded terrace, an abrasion plane, and well-rounded beach material are formed.

The waves which break diagonally take the beach material along the coast, and in areas with diminishing wave energy this material is deposited and a broad beach is formed (Figures 6 and 8).

Where the waves reach the tephra slopes, the development is principally the same, but here the waves only need to wash out the loose material at the foot of the slope; thereafter the upper part of the slope slides (Figure 11). Sand and rubble is removed very quickly.

The great energy of wave turbulence causes small particles to move high up in the water where they are suspended and ultimately deposited far from the coast. In this way material which is finer than sand and rubble is sorted out.

The angle of incidence and the size of the waves varies with the passage of low pressure areas which move across the North Atlantic. In this manner the locus of strongest abrasion and direction of the transport of material along the coast are changed. For long periods of time, relatively constant patterns in the direction of the wave energy can be seen owing to the repeated pattern of the direction and force of the wind and the extent of the water surface upon which the waves are generated.

At Surtsey there is a balance between the east and west components of the distribution of wave energy. Northern winds have relatively low frequency and the limited water surface between Iceland and Surtsey prevents the development of the largest waves which could be created by a certain wind force. These circumstances lead to the fact that the wave attacks are greatest on the south coast of the island, that the material transport along the east coast and the west coast of the island is towards the north, and that the material is deposited on the island's northern shore. In this manner the northern tip of the island has been formed.

Another proof of the east-west balance of wave energy south of Iceland is apparent on the coast of the mainland. The coast consists of extensive deltas



**Figure 7. The Northern Point
Viewed from the East**



**Figure 8. The Western Shore Terrace
and the Tephra Cliff of Surtur Junior**



Figure 9. Sanddrift on the Northern Point

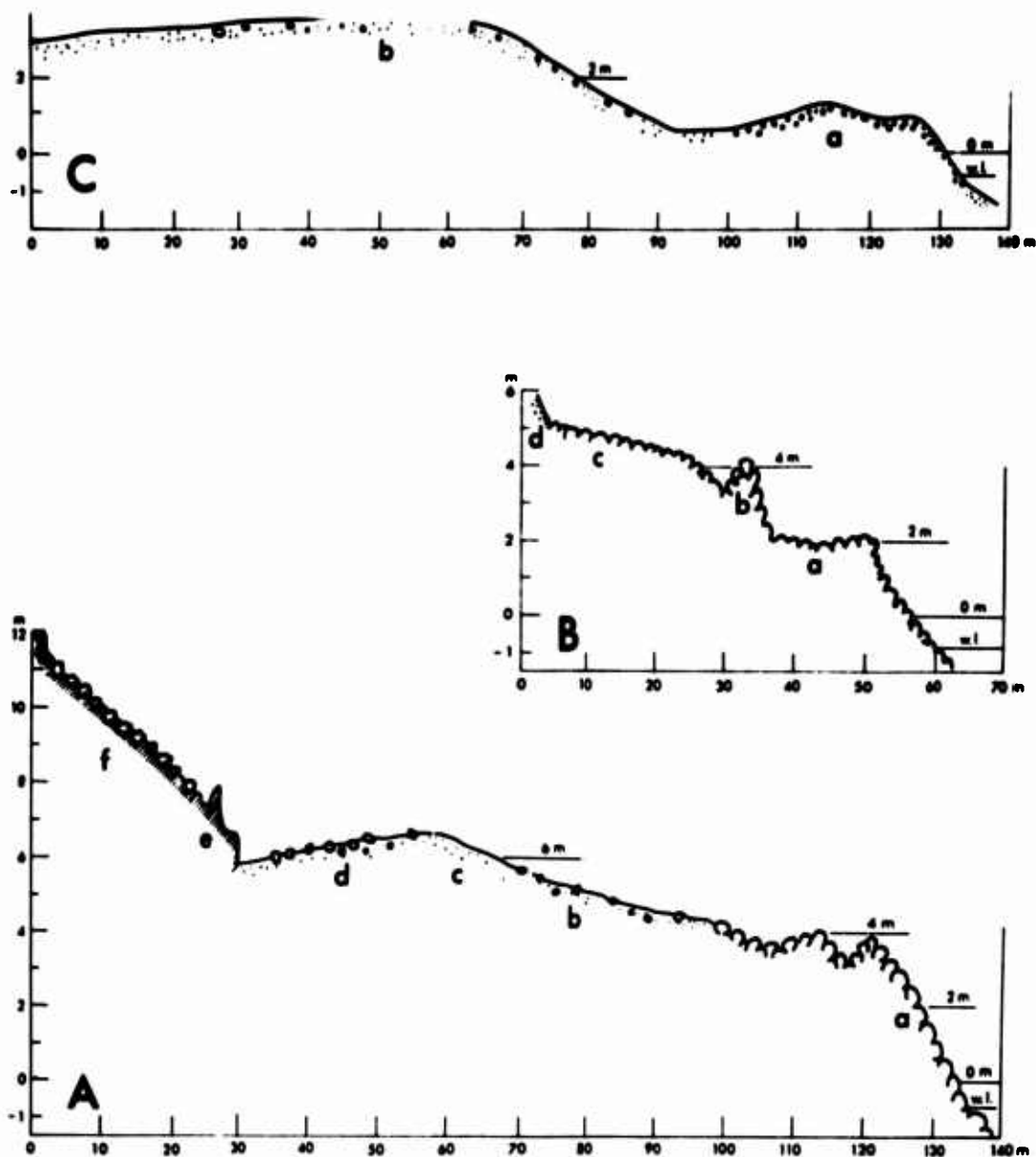


Figure 10. Shore Profiles Levelled in June 1968. Note: 0-level of the height system is 1.5 m above mean sea level. A. Profile from the southeastern coast. a, well-rounded boulders 0.5 - 1.5 m in diameter. b, sand, gravel and cobbles. c, sand. d, sand with scattered angular cobbles and boulders. e, lava cliff. f, angular boulders, about 0.5 m in diameter, thrown up by waves. B. Profile from the western terrace below Surtur II. The material is well-rounded boulders 0.3 - 1.0 m in diameter. a, summer berm. b, beach ridge. c, winter berm. d, talus of Surtur II. C. Profile from the eastern shore of the northern point. a, summer berm of gravel and small cobbles. b, winter berm of sand with scattered pebbles. Swash of storm waves sweeps over the crest. Note the inland dip of the surface

formed by glacial meltwater streams without specific dominance of any particular direction of wave transport. This means that the coast has been built out with the coast line orientation in balance with the distribution of wave energy.

5. CURRENT PROBLEMS AND INVESTIGATIONS

5.1 The Magnitude of the Retreat of the Cliff and its Variation with the Characteristics of the Material and their Exposure to Waves

Lava of different structure has varying resistance to the effect of the waves. Thin beds of lava intercolated with veins of brittle crusts or tephra are easily broken. The lava which has hardened slowly in tunnels under the crust shows the most resistance. The yearly variations of wave energy are reflected in the retreat of the coastline. From the summer of 1967 until the summer of 1968 the retreat was very great on the south coast (Figure 12). The 12-15 meter high cliff retreated a maximum of 140 meters and an average of about 75 meters. For the most part this retreat occurred during the five months after December, 1967. Altogether about two million cubic meters of lava have been eroded from this coastline, that is to say an average of about 13,000 cubic meters per day during the active period.

The retreat is going to be followed by comparisons of aerial photographs and by direct measurements from benchmarks. The development should also be correlated with meteorological data.

5.2 The Greatest Depth of the Effect of the Waves on the Ocean Floor

In spite of the extensive studies that have been carried out concerning wave dynamics since the amphibious operations of the Second World War, there are no accurate data on the depth of wave action. The plateaus of Surtla, Syrtlingur and Jólnir, which have been eroded by waves, offer unique possibilities for study of this problem. According to the depth measurements of the summer of 1967, the highest part of Jólnir lay at a depth of 13.1 meters and the depth of a large part of the plateau fell below 15 meters. Through echogram research and diving during the summer of 1968, the minimum depth at that time was determined to be 19 meters and large parts of the plateau were at depths of 22-24 meters.

The northern part of Syrtlingur had apparently changed only slightly, but Surtlá's plateau, which lay at a depth of 31 to 34 meters during the summer of 1967, had been lowered to 40 meters (Figures 3 and 16).

Another detailed survey of the submarine plateaus should be taken. The maximum waves which could occur can be estimated approximately by meteorological data, but a definite correlation between the size of the waves and the effect

on the ocean floor can be shown only through the emplacement of self-registering instruments, which measure height of the waves, periodicity of the waves, horizontal component of wave oscillation, and tidal currents. Instruments which are suited for this task do exist; the use of them is merely a question of cost. Studies of other submarine cones in the area should be undertaken for comparison.

5.3 Relation Between Exposure to Waves, Beach Material and Coastal Morphology

There are now three beach areas on Surtsey, on the one hand the terraces of the east coast and the west coast with much coarse material and the northern peninsula upon which mainly sand and rubble accumulated because of low wave energy.

The development of the terraces is heavily dependent upon the exposure to waves. This explains, for example, why the highest terrace level formed during the winter of 1968 declines on the east coast from 6.5 meters above sea level in the southern part to only 4.1 meters in the northern part. The size of the material also diminishes markedly towards the north. The western terrace is dominated by diagonally approaching waves which are not deflected, whereas the water depth is great right up to the beach. This coast is formed by a series of diagonally standing banks (Figure 11).

The location of the northern point is not fixed. The position of the point changes alternately from east to west. Beach material is thus transported over steep submarine slopes and lost. If not enough material is transported from the east coast and west coast, the part of the northern point lying above water is going to diminish. In spite of the great erosion that occurred last winter on the southern part of the island, the total area of the island has not been significantly changed.

The point has been exposed more and more as it has been built up. The built up banks therefore have become higher and higher and the surface of the point slopes inward towards the land (Figure 10). During a storm the banks are flooded and the inner parts of the point are filled with water. Last winter's high water mark on the southern side of the point, where it is bordered by the two volcanic cones, is clearly distinguished by floating seaweed stranded 3.3 meters above sea level. Floods mean that material from the beach is transported and deposited inside the point. Changes in the point are being followed repeatedly by measurements of profiles in a fixed coordinate system.

5.4 The Morphology of the Ocean Floor Next to the Beach and the Sorting of Material

The highest energy change in wave movement occurs when the incoming waves meet the outgoing water from the beach. Here a large part of the directed wave current is changed into chaotic turbulence. The coarseness of the material

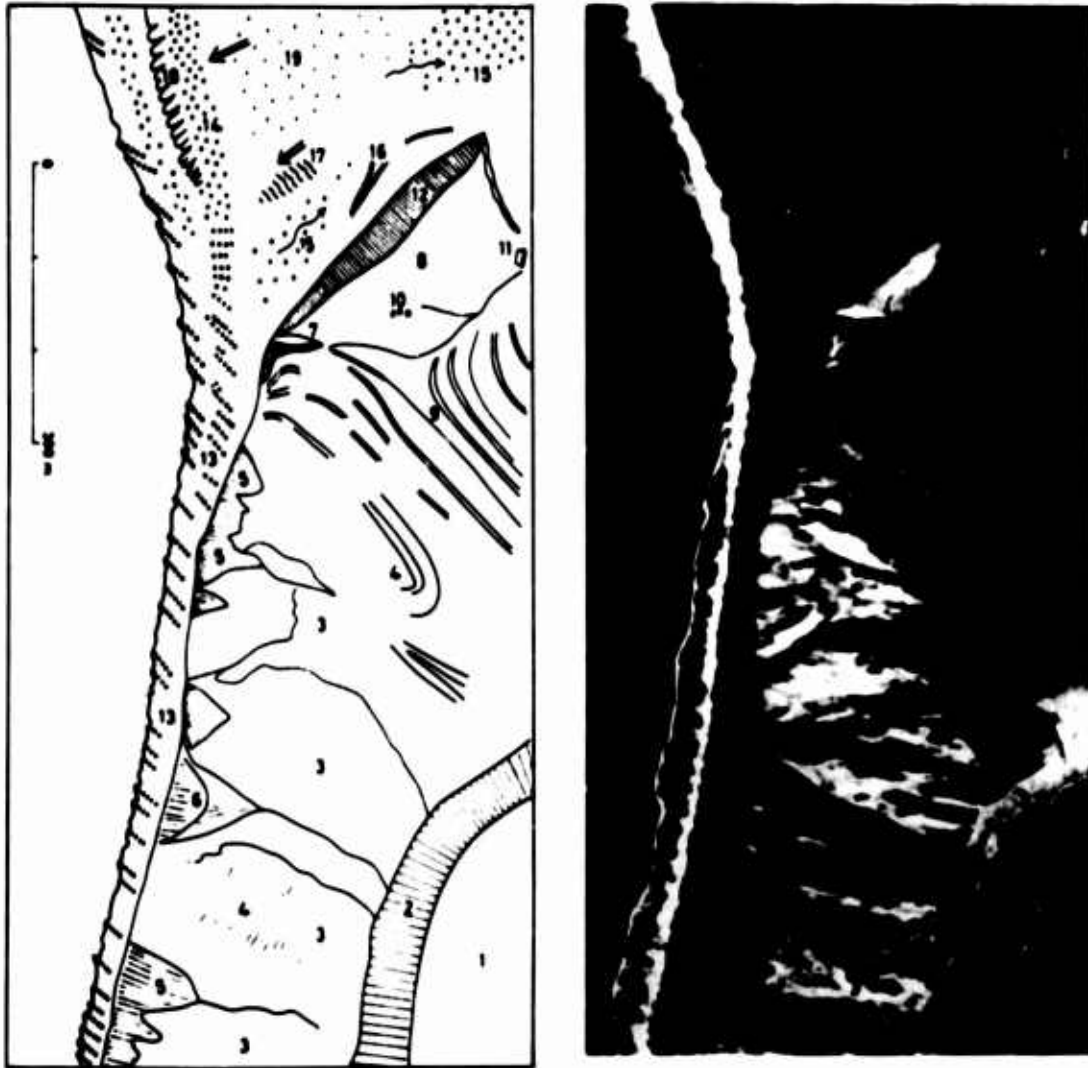


Figure 11. Geomorphological Elements of the North-western coast. 1, lava in the crater of Surtur Junior. 2, tephra wall in the crater. 3, slump scars. 4, sediment structures in the tephra. 5, talus cones. 6, abrasion in talus. 7, mudflow ravine. 8, large subsided slide block. 9, mudflow tracks. 10, meteorological instruments. 11, research station. 12, abraded cliff. 13, beach ridges. 14, extension of western boulder terrace. 15, cobbles and boulders swept in during storms, arrow marks transport direction. 16, erosion scarps. 17, low dunes, arrow marks wind direction. 18, sand drift. 19, deflation surface

increases within this region only to diminish abruptly thereafter. In this zone a maximum of swirling of the material and sorting of size occurs. So far it has not been possible to study the material and morphology of this zone more closely. Since the outboard-motor-powered rubber boat stationed on Surtsey did not function satisfactorily and capsized much too often in the swirls, all the diving work was carried out with a fishing boat from Helmaey and that could not come near the coast. Examinations should be undertaken by diving from a rubber boat which is tied by a line to the shore and to a larger boat lying at anchor, which is assisting it. In the same manner the selective erosion of the lava area's abrasion planes should be studied more closely.

5.5 Morphology of the Submarine Slopes

We have already mentioned the steep slopes off Surtsey's northern point. The diving research which was undertaken during the summer of 1968 showed that these slopes were steep enough to cause constant avalanching. The material was mainly sand and rubble. There were also rows of boulders oriented in the direction of the inclination of the slope, sliding down the slope in a boulder stream (Figure 13). Echo soundings along the coast showed a more detailed morphology of avalanche scars than could be reproduced in Figure 15, which is based on the soundings taken at right angles to the coast in 1967. A detailed re-mapping of these slopes should be undertaken.

Off the southeast coast, the bathymetric map (Figure 3) shows curve-formations which could indicate hardened lava streams in the submarine slope. During diving operations in this area only steep slopes with enormous boulders loosely piled upon each other were observed. The diver, lic. Alexandersson, described these boulders as having the form of cottages. Further examination in this area should concentrate on the stability of these steep slopes consisting of boulders. Cooperation with marine biologists is therefore of value in order to determine the rate of growth of the vegetation. (See Figure 14).

6. CONCLUSION

Because the high wave energy, the depth conditions and the material promote rapid development, Surtsey offers unique possibilities for studying the processes of coastal morphology. The processes in principle are so general that the correlations found apply to other coast areas where the coastal erosion and steps for the protection of the coast are vital problems in practical economy. In Sweden these problems occur only locally, but these processes have high relevance for areas near beaches because sand and gravel pits are about to be



Figure 12. The Southeastern Coast on July 6, 1968 and the Coastline of July 1967 (white contour)



Figure 13. Boulder Stream in the Western Submarine Slope of the Northern Point. Dip of sand surface is at angle of repose. Depth 25 m



Figure 14. Vegetated Boulder in the Steep Submarine Slope of the Southern Coast. Depth 35 m

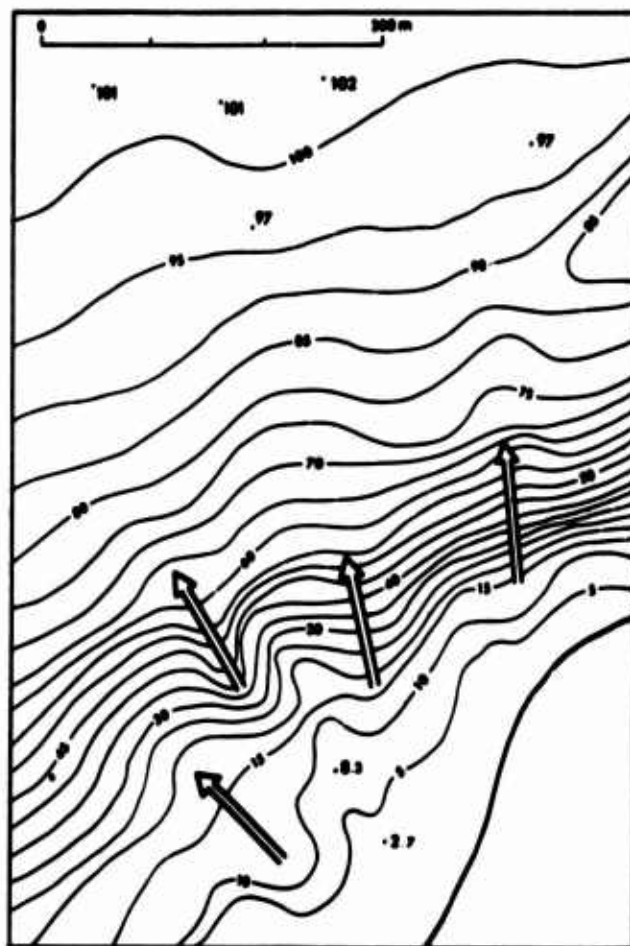


Figure 15. Avalanche Scars (arrows) in the Submarine Slope of the Northern point. Depth contours indicate debris tongues at the base of the slope

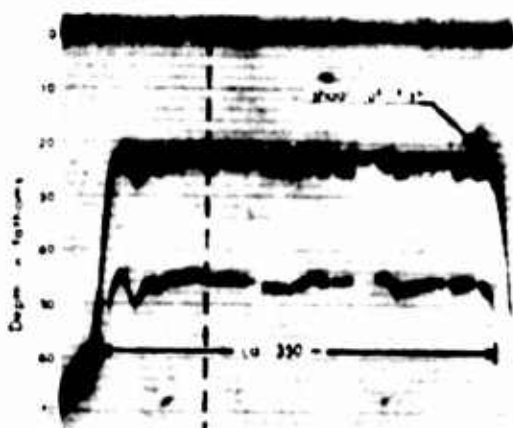


Figure 16. Echogram of the Surtla Shoal from WSW - ENE Recorded on June 28, 1968. According to soundings of July 1967 (Figure 2) waves and currents have lowered the plateau from 18 to 22 fathoms in one year

exhausted and sand and gravel operators are more and more interested in the underwater material off the beaches. The exploitation of these resources can not be permitted without first finding out about the damaging effects this can inflict upon the nearby ocean floor and beaches.

Earlier geochemical, geophysical and biological research on Surtsey was subsidized by major American research grants. The changed policy of the USA has led to a great reduction in the amount of money given to Surtseyjarfélagið (The Surtsey Research Society). It seems advisable that the investigations on Surtsey should be continued within the realm of Scandinavian cooperation.

7. SUMMARY

Investigations on the shore and offshore morphology of the volcanic island of Surtsey off the southeastern coast of Iceland are reported. The volcanic activity that started as a submarine explosion in November 1963 ended in June 1967. A photogrammetric map of the island is in preparation. During the winter 1967/68 there was a rapid retreat of the lava cliff on the southern coast. The cliff is 10 - 15 m in height. The maximum retreat was 140 m and the average retreat about 75 m. The amount of lava removed by erosion is estimated at 2 million cubic meters.

The shoals of former cinder-cone islands (Surtla, Syrtlingur, and Jólnir), contemporaneously built up, were found to have been abraded during the last winter. The plateaus of Jólnir and Surtla had been lowered several meters (Figures 3 and 16).

The submarine slopes of Surtsey were investigated by SCUBA diving down to a maximum of 40 m in depth. The sandy material of the slopes of the northern point is deposited at the frictional angle of repose. There is active avalanching on these slopes. On the slopes of the southern coast coarse angular blocks dominate. Some of the blocks are more than 5 m in diameter. The future development of the island will be recorded by aerial photography and successive surveys of fixed traverses.

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